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# Thomas Young's contribution to visual optics: The Bakerian Lecture “On the mechanism of the eye”

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Thomas Young (1773-1829) carried out major pioneering work in many different subjects. In 1800 he gave the Bakerian Lecture of the Royal Society on the topic of the “mechanism of the eye”: this was published in the following year (Young, 1801). Young used his own design of optometer to measure refraction and accommodation, and discovered his own astigmatism. He considered the different possible origins of accommodation and confirmed that it was due to change in shape of the lens rather than to change in shape of the cornea or an increase in axial length. However, the paper also dealt with many other aspects of visual and ophthalmic optics, such as biometric parameters, peripheral refraction, longitudinal chromatic aberration, depth-of-focus and instrument myopia. These aspects of the paper have previously received little attention. We now give detailed consideration to these and other less-familiar features of Young's work and conclude that his studies remain relevant to many of the topics which currently engage visual scientists.

**Keywords:** accommodation, astigmatism, biometry, chromatic aberration, gradient index, historical, monochromatic aberration, optometer, peripheral refraction, spherical aberration, Thomas Young

## Introduction

The Englishman Thomas Young is now one of the world's most famous scientists. A polymath, he made major contributions to many fields, including the nature of light and sound, vision and hearing, mechanics, hydrodynamics, linguistics and physiology. He is particularly well known for his demonstration of the wave nature of light (Young, 1804), his contribution to the decipherment of Egyptian hieroglyphics (Young, 1823a), his explanation of the focusing mechanism of the eye (Young, 1801), the trichromatic theory of colour vision (Young, 1802b), the elasticity of bodies (Young's modulus) (Young, 1807b) and capillary action (Young, 1807a).

In 1793, when he was only 19 years old, he presented to the Royal Society his paper “*Observations on vision*” (Young, 1793). This mainly dealt with “accommodation”, a term which had been coined by Porterfield (1738) to describe the ability of the eye to see clearly at a range of distances. It discussed the different theories as to the cause of accommodation and presented evidence which Young interpreted to mean that the lens behaved like a muscle to change its shape. Young gave a successor, and much more thorough, paper in 1800 that was published the following year (Young, 1801). This was the first of Young's three Bakerian Lectures. This series of annual Royal Society lectures, which still continues, had originated in 1775 in a bequest of £100 from Henry Baker for “...an oration or discourse ... on (some) part of natural history or experimental philosophy...” (Royal Society of London, 2010). The majority of this later 1801 paper “*On the mechanism of the eye*”

concerned the measurement, origins and effects of accommodation. Young measured refraction and accommodation with his own variation of the optometer developed by Porterfield (1738). He considered the different possible origins of accommodation and confirmed that it was due to change in shape of the lens rather than in change in shape of the cornea or an increase in axial length. He also described the astigmatism of his own eye.

However, in addition to the work in accommodation and astigmatism, this second paper dealt with many other aspects of visual and ophthalmic optics, such as biometric parameters, peripheral refraction, longitudinal chromatic aberration, depth-of-focus and instrument myopia. These important early contributions to the development of studies in visual optics are much less widely known than Young's work on accommodation. Many of the topics that he discussed remain under active study at the present time. In this critique we take an in-depth look at Young's contributions to visual optics in light of our present understanding.

Young's paper is divided into twelve sections. Following three sections of Introduction, in section IV, he developed a number of equations which were used to support his calculations and theories. This important geometrical optics work will not be discussed here but, among other quantities, it allowed Young to calculate the positions of the two astigmatic focal lines and circle of least confusion for off-axis image pencils and spherical refractive surfaces. In later parts of the paper he made use of these equations in the case of the eye.

Young used the dimension of inches for distances and focal lengths. In the present work, while retaining his Imperial values, we have converted these values to millimeters for distances and dioptres for lens powers and magnitudes of accommodation.

## Contributions to visual optics

### 1. Young's optometer

Central to Young's work was the use of his own design of optometer. Porterfield (1738) had earlier coined the term "optometer" and constructed one using the Scheiner principle. Essentially this consisted of two narrow vertical slits in a metal plate, separated by a distance less than the pupil diameter. The plate was held close to the eye and a vertical slit object illuminated by a candle was observed in a dark room. By moving the object to various distances, the near and far points could be established, provided that these lay in front of the eye and within the dimensions of the room. For far points, it was thus only suited to measurements on myopes.

Young described his own optometer, based on that of Porterfield, in section V of his 1801 paper: a photograph was provided by Levene (1977) and a sketch is provided in Fig. 1. As in Porterfield's instrument, its principle is that an object conjugate with the retina is seen singly when observed through two apertures close to the eye and separated by less than the diameter of the pupil, but out-of-focus objects closer to or farther away from the eye appear doubled. Young used slit apertures whose spacing and width could be altered "so that each observer may choose that which best suits the aperture of his pupil" (p. 35). However, rather than lying in a single frontal plane, his target was a line, running the length of a bar resembling a flat ruler about 200 mm long, and slightly below the eye. Due to the doubling of out-of-focus objects, the single target line was seen as two obliquely crossing lines, with the object position conjugate to the retina corresponding to the crossing point of the lines. A moveable index marker on the optometer bar was used to mark this point. To adapt the instrument for "*presbyopic*" eyes, meaning in the terminology of the period the hypermetropic eyes that often occurred in older people rather than our present understanding relating to loss of accommodation, a 4" focal length (nearly 10 D) lens was placed near the eye. Numbers on several scales marked on the bar corresponded to the focal lengths of the correcting glasses required. Young provided scales for the focal lengths of lenses required for reading at different distances (8", 12" and 18": 200, 300 and 450 mm).

FIGURE 1 ABOUT HERE

By rotating the optometer bar and slits about the line of sight, refraction along different ocular meridians could

be explored. For example, to measure refraction along the vertical meridian, the instrument would be rotated until the slits were horizontal.

As will be discussed below, Young used his optometer to study refraction (including astigmatism), accommodation, spherical aberration and longitudinal chromatic aberration, and to make observations on depth-of-focus and instrument myopia. To estimate spherical aberration, he used four slits within the pupil, rather than two.

### Commentary

The engineer and inventor Hawkins (1827) measured his own astigmatism with Young's optometer and recommended its use to providers of spectacles, and Tscherning (1900) continued the exploration of ocular aberration with a Young's optometer. Apart from these studies, we are not aware of instruments similar to Young's design being used since his time (i.e. instruments based on observation of a line which appears as a cross). We do not know if a tilted line object and its crossed appearance have any benefits compared with the simpler case in which the object has a single distance. One problem with Young's optometer, as with other applications of the Scheiner disc principle, is evidently that its precision is poor if the pupil diameter is small. However, the Scheiner disc principle has since been employed in a variety of both subjective and automated optometers and it can be considered that it continues to be used in Hartmann-Shack and laser raytracing aberrometers, as these rely on isolating small regions in the pupil (Atchison, 2008). Many later optometers use the Badal principle (Badal, 1876) in which a positive lens is placed at its focal distance from the eye, with the consequence that an object viewed through the optometer appears always to be the same size (the angular subtense of the image is unaltered) and the scale in dioptres is linear with distance from the lens.

The optometer with two slits does not give information about the higher-order aberrations of the eye; this matter is addressed in the section on monochromatic aberrations.

### 2. Biometric measurements of the eye

In section VI of his 1801 paper, Young presented a number of measurements of his own left eye and used these to derive other optical quantities. He stated (p. 38) "*Being convinced of the advantage of making every observation with as little assistance as possible, I have endeavoured to confine most of my experiments to my own eyes; and shall, in general, ground my calculations on the supposition of an eye nearly similar to my own. I shall therefore first endeavour to ascertain all its dimensions, and all its faculties*". Although it is reasonable that he should wish to examine his own eye as closely as possible, his reluctance to make use of help from others in making the measurements is harder to understand. His determination

not to seek assistance meant that, when measuring his left eye, his right eye had to be used to make the measurements. Large eye movements were often required in order for observations to be made with this eye.

He measured the corneal diameter (presumably visible iris diameter) in both the vertical (45/100" or 11.4 mm) and horizontal (49/100" or 12.4 mm) directions. He obtained the sagitta (or "versed sine") from the protrusion of the corneal apex from the limbal plane in the vertical meridian (11/100" or 2.79 mm). Using, apparently, the mean of the two corneal diameter values and the sagitta, he calculated the radius of curvature for the anterior cornea to be 0.31" (7.9 mm). Some indication of the difficulties in making these observations can be gained from his description of his method for determining the versed sine: *"I looked with my right eye at the image of the left, in a small speculum [mirror] held close to the nose, while the left eye was so averted that the margin of the cornea appeared as a straight line, and compared the projection of the cornea with the image of a cancellated scale held in a proper direction behind the left eye, and close to the left temple."* (p. 38). The problems inherent in this procedure make it surprising that Young was not too far from a correct value.

For calculation purposes, Young assigned a refractive index of 4/3 to the cornea and internal media. The length of the eye was measured with a pair of compasses modified by having a small key fitted to each compass point. Young adducted (turned in) his eye as much as possible and the rings of the two keys were placed outside the cornea and into the external angle of the eye, as close to its axis as possible. The pressure at the back of the eye produced an entoptic ring phosphene which he kept in the centre of the visual field. He subtracted 0.03" (0.8 mm) to allow for the coats of the eyes to get an internal axial length of 0.91" (23.1 mm). Using his modified pair of compasses, Young also determined an external transverse diameter of the eye of 98/100" (24.9 mm).

Young described asymmetries in the eye, including those of the cornea, pupil, lens (13° tilt to account for his astigmatism) and the distances of the fovea and optical nerve from the "visual" axis. The pupil eccentricity changed depending on the pupil size. His estimate for the range of his entrance pupil diameters was 0.13 to 0.27" (3.3 mm to 6.9 mm) and he noted that the iris appears larger due to its magnification by the cornea.

He then turned to the lens and its effective refractive index. He assumed that the distance from the cornea to the lens was 0.12" (3.0 mm), slightly greater than the corneal sagitta (0.11"). He assumed anterior and posterior lens radii of curvature as 0.3" and -2/9" (7.6 mm and -5.6 mm), respectively, based on a 1730 paper by the Frenchman Petit (1730) which also gave an axial thickness estimate of 0.18" (4.6 mm). From the radii of curvature proportions, Young determined the lens optical centre, the point on the axis through which a ray passes that has the same orientation on both sides of the lens, to be 0.1" (2.5 mm) inside the lens and 0.22" (5.6 mm) from the vertex of the cornea. He

then made use of the fact that, with his optometer, he saw clearly at a distance of 10 inches (254 mm) from the cornea with relaxed accommodation and for rays in the vertical meridian. The image was then in focus on his retina, which as discussed earlier he estimated lay 0.91" behind the cornea, and thus 0.69" behind the optical centre of the crystalline lens. Treating the latter as thin, he found that its principal focal distance was 1.73 inches (43.9 mm). Further calculation, with allowance for the lens thickness, led him to the conclusion that the equivalent refractive index of the lens was 14/13 that of water, i.e. 1.436. Interestingly, he followed this with a practical measurement using a recently excised human lens in water, when he found a value of 1.400. He mused on the possibility of post mortem changes but pointed out that his original estimates were based on the concept of a homogeneous lens, whereas the crystalline has a gradient of refractive index, the index being higher at the centre, so that the index gradient will confer additional power. Taking account of such effects he estimated that the actual refractive index at the centre of the lens was about 1.41, but that the equivalent index of the whole lens was about 1.44. These values are not very different from modern estimates (Jones, Atchison, Meder, & Pope, 2005).

### Commentary

Although many earlier authors had drawn the eye in section, none had attempted to fully quantify the various ocular parameters. Young appears to have been the first to estimate the corneal radius of curvature in a living eye, although Petit (1728) had measured enucleated eyes and found a typical radius of curvature of about 8.5 mm. One continues to wonder, however, why Young insisted on carrying out all the measurements on himself, in spite of the difficulties and probable inaccuracies that this introduced. He was, for example, good friends with Wollaston (of Wollaston prism fame) and could presumably have asked for his assistance.

It is interesting to compare Young's paraxial values for the ocular biometric parameters of his own eye with those of the simplified Gullstrand No.2 schematic eye as modified by Emsley (1955) (Table 1, Figure 2). As can be seen in the Table, there is broad, but by no means exact, agreement on the magnitudes of the various quantities. It must be remembered that Young was presenting data for a single myopic eye, whereas the Gullstrand-Emsley eye is supposedly representative of the typical characteristics of a large population of emmetropic eyes.

### FIGURE 2 ABOUT HERE

Young's estimate of internal axial length at 0.91" (23.1 mm) seems short for someone who was about 5 D myopic (> 25 mm expected) (Atchison et al., 2004; Carroll, 1981; Chau, Fung, Pak, & Yap, 2004). Given the presence of extraocular muscles, nerves, blood vessels and orbital fat, it is surprising to us that few authors seem to have questioned

that Young could measure axial length to any reasonable accuracy, although he himself concedes (p. 38) “*With an eye less prominent, this method might not have succeeded*” and Helmholtz (1909) remarked (p. 159) “*Thomas Young must have had somewhat protuberant eyes, as may also be inferred from other experiments which he describes. When the above experiment was made by the writer [Helmholtz], only one edge of the retinal impression extended as far as the place of clearest vision ...*”

For the lens, the radii of curvature are too small, the anterior chamber depth is too small, and the lens thickness is too large for someone of Young’s age. Petit (1730) himself gave data for excised lenses from eyes between 12 and 65 years. Young seems to have selected values corresponding to eyes of his own age: his values are very similar to those obtained from regression line fits to Petit’s data as a function of age. As is now well known, excised lenses take up a fully accommodated form due to their freedom from the constraints applied through the zonule so that, even if accurately measured, the anterior radius of curvature and thickness would be expected to be inapplicable to the condition for which Young carried out his calculations, where lenticular accommodation was assumed to be relaxed. The assumption of flatter lens radii of curvature would, of course, have affected a number of other parameters derived from them. As Levene (1977) and others have noted, Young’s calculation of corneal radius assumed that the cornea is spherical, rather than flattening towards its periphery (Atchison & Smith, 2000), and depends on the use of his value for the vertical diameter. It is not clear why, given his discovery of his own astigmatism, Young did not attempt to determine his corneal radius of curvature in both the vertical and horizontal meridians but instead derived a mean value: it may be that his conviction that astigmatism was still present when the corneal power was neutralised (see below) made him reject this obvious step; see Levene (1977) for discussion. Using each of the two visible iris diameters, and assuming the sagitta for the vertical meridian (2.79 mm) applies also for the horizontal meridian, derived vertical and horizontal anterior corneal radii of curvature are 7.2 and 8.3 mm, respectively. With a keratometer index of 1.333, this difference in radii corresponds to nearly 6 D of with-the-rule corneal astigmatism, much larger than that actually measured in Young’s eye (see point 3. below).

Figure 2 shows a schematic eye constructed using Young’s measured and assumed parameters. Paraxial raytracing indicates that, for an object at 10” (254 mm), i.e. at Young’s assumed far point, the axial length is only 0.07 mm short for the unaccommodated case, so that Young’s calculations were correct given the various rounding errors in his measurements of dimensions. Young estimated that the stop diameter range was 8% smaller than that for the entrance pupil, but most schematic eye estimates suggest a difference of about 13% (Atchison & Smith, 2000).

Parameter	Young's eye	Gullstrand-Emsley eye
Aqueous/vitreous index	4/3	4/3
Lens index	1.436	1.416
Corneal position (mm)	0	0
Anterior lens pole position (mm)	3.0	3.6 (3.2)
Posterior lens pole position (mm)	7.6	7.2 (7.2)
Retinal position (mm)	23.1	23.9
Corneal radius of curvature (mm)	7.9	7.8
Anterior lens radius of curvature (mm)	7.6 (5.3)	10.0 (5.0)
Posterior lens radius of curvature (mm)	-5.6 (-3.8)	-6.0 (-5.0)

Table 1. Comparison between the ocular biometric parameters as established by Young for his left eye and assumed in the Gullstrand-Emsley eye (Emsley, 1955). Both eyes are assumed to be unaccommodated. The parameters for Young’s eye have been rounded to the nearest 0.1 mm (for raytracing no rounding was done when parameters were converted from inches to mm). The bracketed figures indicate the assumed changes in the crystalline lens required to produce 10 D (Young) and 8.6 D (Gullstrand-Emsley) of accommodation.

3. Refraction and astigmatism of the eye

In section V of his 1801 paper, Young described the refraction of his left eye. With the slit apertures of his optometer oriented vertically and horizontally, the refraction distances were 10” and 7”, respectively, corresponding to a correction of -3.9 DS/-1.7 DC x 90. Previously Young had been unaware of and not inconvenienced by this “imperfection”. A colleague, the London instrument maker and optician William Cary, mentioned to him that he too had noticed this deficiency and that it could be corrected by a [concave] lens held obliquely with (p. 40) “*the too great power of the eye in the direction of that inclination*” i.e. a negative lens tilted about the horizontal meridian. By observing a point source at varying distances, Young was able to sketch the two focal lines and other through-focus forms of point-spread function produced by his refractive error (Figure 3). He associated the striations in the markedly out-of-focus images with the lens fibres.

FIGURE 3 ABOUT HERE

Commentary

Young wrote in his autobiographical sketch: “*He felt some inconvenience in society from being a little short sighted ...*” (Hilts, 1978). If Young’s refraction with his optometer was accurate, he was more than a little short-sighted!

Young was the first to measure on-axis astigmatism. The remedy of tilting a spectacle lens to correct astigmatism would not seem to be very practical in Young’s case: with a -3.6 D lens of refractive index 1.5 a tilt of 34° would be



required. However, in a letter to the famous astronomer George Airy he wrote (Levene, 1977) *“Did you ever read my account of my own crystalline lens? which being placed obliquely gives the same character to the focus that yours possess, but mine is sufficiently corrected by holding my concave eyeglass obliquely ...”*. This suggests either that the power of the concave lens was greater than given by the optometer measurement or that he had less astigmatism than given by the measurement.

Although he did not determine the principal radii of curvature of his crystalline lens, Young wrote that the deficiency was not in the cornea because it continued to exist when (p. 40) *“the effect of the cornea is removed by a method to be described hereafter”* [the reduction of corneal power by inserting it in a fluid described in section VIII; see next point]. Using the formula that he had derived in his Section IV for refraction at oblique incidence, he calculated that the crystalline lens tilt producing this astigmatism was  $13^\circ$  about the vertical meridian. We know now that in most cases of astigmatism greater than about 0.5 D, and as described by Javal’s rule, the cornea is the major contributor (Javal, 1890).

Assuming the crystalline lens to be thin and that all its refraction takes place at the front surface location, the  $13^\circ$  tilt given by Young does indeed give 1.7 D at the lens, but would give only 1.2 D cylinder referenced to the corneal plane. A tilt of  $15^\circ$  would be needed to match his astigmatism of 1.7 D. Both of these angles are much higher than is usually reported. As his thin lens power is 32D, this is not because the power was being underestimated.

Twenty six years after Young’s paper, Hawkins (1827) measured astigmatism of both his eyes and considered correcting it with a cylindrical lens. George Airy went one better, measuring and correcting astigmatism in his left eye using a lens with a cylindrical front surface (Airy, 1827). Goodrich in the United States followed shortly afterwards (Levene, 1977).

#### 4. Accommodation and its origin in the crystalline lens

Much of Young’s paper was concerned with showing that the accommodation of the eye is caused by changes in lens shape. As it is the best known aspect of the paper, we shall not cover this at length. Young inferred that the origin of accommodation lay in a change in lens shape by eliminating other possibilities, such as changes in corneal curvature or ocular length, rather than by direct measurements on the lens itself.

In section VII of his 1801 paper, Young measured amplitude with his optometer in at least five subjects, including himself and William Hyde Wollaston (like Young, a multi-faceted scientist). Estimates of amplitude for these two subjects, aged approximately 27 years and 34 years at the time, were 10 D and 7D, which seem to be overestimates.

Young calculated that, on its own, his corneal radius of curvature would have to decrease by 19% to account for his

10 D amplitude of accommodation. In section VIII of his 1801 paper, he found that accommodation caused little or no change in corneal shape or radius. This conclusion was based on a series of experiments which showed that, with accommodation, no change in size occurred in images reflected from the cornea (Purkinje image I). He therefore dismissed the possibility that increased corneal power was the source of accommodation. In support of his methodology, he noted (p. 57) *“Make a pressure along the edge of the upper eyelid with any small cylinder, for instance a pencil, and the optometer will show that the focus of the horizontal rays is a little elongated, while that of the vertical rays is a little shortened; an effect which can only be owing to a change of curvature in the cornea. Not only the apparatus here described, but even the eye unassisted, will be capable of discovering a considerable change in the images reflected from the cornea, although the change be much smaller than that which is required for accommodation of the eye to different distances ...”*

Next he described the famous experiment in which accommodation was measured when the eye was immersed in water to (largely) neutralise the corneal power. A 0.8” focal length lens was placed over the end of the water container; he wrote that this had an effective focal length of 1.6” (25 D) to compensate for the lack of effective corneal power. He found that neutralization of corneal power did not prevent accommodation, which had a similar magnitude to that found before insertion of the cornea in water. In his opinion, so conclusive was this experiment in ruling out the cornea as the site of accommodation that he wrote (p. 58) *“After this, it is almost necessary to apologize for having stated the former experiments; but, in so delicate a subject, we cannot have too great a variety of concurring evidence.”*

Considering next the possibility of accommodation being caused by an increase in axial length, Young calculated that a movement of the retina of 0.135” (3.43 mm) would be required to achieve his observed 10D amplitude of accommodation. In section IX of his paper, he reasoned that this would reduce the transverse diameter of the eye, but measurement showed no changes. He then used a variant of the same method that he had used earlier to measure axial length to show that no change in length occurred as a result of accommodation change. He effectively clamped his inwardly-turned eye between two rings, one (*“a strong oval iron ring”*) round the cornea and one (the ring of a key) close to the posterior pole, so that pressure from the latter produced a phosphene overlapping the foveal area. The prevention of any increase in eye length would have resulted in an increase in pressure, which Young believed would increase the phosphene’s extent. However, no change of the phosphene size was seen during the effort of accommodation.” The accommodative amplitude was unaffected by the immobilisation of the eye. Other experiments investigating the sizes of retinal images found no change in apparent object size with accommodation. In one experiment an after-image was compared with a fixed scale, and in the other two candles

were observed, with one image falling on the fovea, the other on the blind spot.

In section X of his paper, Young considered how the lens might change shape with accommodation after finding that aphakes could not accommodate when measured with the optometer (most of Young's subjects were presbyopic).

He noted (p. 53) that if his crystalline lens became a sphere, its diameter would be about 0.28" (7.1 mm) and, assuming that the position of its anterior pole was unchanged, the eye would have perfect vision at 1.5" (38 mm), so that the amplitude of accommodation would be more than double that observed in practice.

On the assumption that "*both the surfaces...undergo proportional alterations in curvature*", Young speculated on page 70 that the radii of curvature of the lens surfaces would need to decrease from 0.3" (7.6 mm) and 0.22" (5.6 mm) to 0.21" (5.3 mm) and 0.15" (3.8 mm), respectively (reductions of approximately 30% each) (Figure 4). To account for the observed changes in spherical aberration with accommodation (see point. 6), the originally-spherical front surface would become hyperbolic and the posterior surface nearly parabolic. These changes would not cause any change in diameter and would give an axial thickness change not exceeding 0.02" (0.5 mm) with the majority of the lens movement occurring at the posterior surface. There is some inconsistency here, since he had earlier suggested (p. 53) that the fully-accommodated anterior and posterior radii would have to change to 0.24" (6.1 mm) and 0.17" (4.3 mm) respectively, and his Figs. 25 and 26 of unaccommodated and accommodated lenses show a decrease in diameter with accommodation (Figure 5).

FIGURE 4 ABOUT HERE

FIGURE 5 ABOUT HERE

### Commentary

We should be thankful that these observations were possible, since they depended on Young being youthful enough (about 27 years old) to have high amplitudes of accommodation and having astigmatism of non-corneal origin. A degree of scepticism about Young's ability to conduct the experiment involving the clamping of the eye is in order.

There were several hypotheses for the origin of accommodation in Young's time. Descartes had already considered that it was due to change in lens shape (Wade, 1998) and this was supported by Porterfield (1738) who noted the requirement of an aphakic patient for different corrections at different distances. Some of the ideas for the origin of accommodation had included contraction of the pupil, change in curvature of the cornea, movement in lens position, and change in eye length. According to

Tscherning (1907), Young's paper showing that accommodation is produced by an increase in curvature of the lens "... *did not produce the slightest effect. So as late as 1851 Arlt, having discovered that myopia is due to an exaggerated length of the eye, concluded that accommodation is also produced by a lengthening of the eye, myopia being a result of working at short distances.*"

As mentioned earlier, Young had first hypothesised that lens shape change is responsible for accommodation in his 1793 paper (Young, 1793). On the basis of the observations of Home (1795) that the aphakic eye of a young patient appeared to retain considerable accommodation and that the cornea appeared to become more curved on accommodative effort, Young had temporarily abandoned it: "... *I shall relinquish them with as much readiness as I have long since abandoned the hypothesis which I once took the liberty of submitting to the Royal Society, on the functions of the crystalline lens.*" (Young, 1800). In his 1801 paper Young wrote in reference to Home's work (p. 23): "... *the results of his experiment appeared very satisfactorily to confute the hypothesis of the muscularity of the crystalline lens.*" However, he recommenced his own studies because of renewed conviction arising from the observations of his colleague Ware of the "*advantage all his patients found, after the extraction of the lens, in using two kinds of spectacles*" (p. 64) and by Porterfield (1738) who had planned but apparently not performed an experiment to ascertain whether aphakes can accommodate. Young attributed Home's observations of 16 D of apparent accommodation to what we refer to as depth-of-focus with a small pupil (see point 8. below). Young conducted experiments on Home's aphakic patient at a later date in the presence of Home and others, and reported (Young, 1823b) "*it appeared that the imperfect eye, from which the crystalline lens had been extracted, possessed no power whatever of altering its focus, while the same tests exhibited a very considerable change in the focal distance of the perfect eye.*"

Regarding Young's speculations about the change in lens shape with accommodation, we now know that most of the change takes place at the anterior surface (Dubbelman, Van der Heijde, & Weeber, 2005; Rosales, Dubbelman, Marcos, & van der Heijde, 2006) rather than the lens surfaces changing proportionally, as assumed by Young. Instead of the lens diameter not changing with accommodation, it decreases at a rate of approximately 0.05 mm/D (our unpublished data using magnetic resonance imaging). Most studies of the positions of the poles find that the majority of surface movement occurs at the anterior surface (Bolz, Prinz, Drexler, & Findl, 2007; Drexler, Baumgartner, Findl, Hitzenberger, & Fercher, 1997; Dubbelman et al., 2005; Ostrin, Kasthurirangan, Win-Hall, & Glasser, 2006). It is likely that the changes in refractive index distribution affect accommodation (Gullstrand, 1911; Kasthurirangan, Markwell, Atchison, & Pope, 2008). It has been established many times that the lens is responsible for accommodation although consideration has been given to changes occurring in corneal shape of up to 0.4 D (Pierscionek, Popiolek-

Masajada, & Kasprzak, 2001) and in axial length of less than 0.1 mm ( $< 0.3$  D accommodation) (Drexler, Findl, Schmetterer, Hitzengerger, & Fercher, 1998; Mallen, Kashyap, & Hampson, 2006). These minor changes may be, at least in part, artefactual due to cyclorotation of the eye affecting the corneal results (Buehren, Collins, Loughridge, Carney, & Iskander, 2003) and assumed refractive indices in the media affecting axial lens results (Atchison & Smith, 2004).

It is of interest that Young's Figs. 25 and 26 (our Figure 5), showing the unaccommodated and accommodated lens in section, suggest a much greater increase in axial thickness than he specifies ("elongation of its axis will not exceed the fiftieth of an inch", p. 70), but perhaps his diagrams give a schematic rather than an exact representation of his views.

Regarding asphericity of the lens surfaces, recent studies show that the asphericities (Q values) become less positive or more negative with increase in accommodation (Dubbelman et al., 2005) and are undoubtedly a factor in changing spherical aberration with accommodation (see point 6). It has sometimes been claimed that Young wrote that the peripheral parts of the lens surfaces flattened during accommodation e.g. (Sheard, 1921-1922; Tscherning, 1907), but he only claimed that the peripheral of the lens surfaces were flatter than the centres of the surfaces: "... and the only imaginable way of accounting for the diversity, is to suppose the central parts of the lens to acquire a greater degree of curvature than the marginal parts" (p. 69).

Our modelling confirms Young's determination that a reduction in corneal radius of curvature of 19% (from 7.9 mm to 6.4 mm) would account for the accommodation. An increase in axial length of 3.7 mm rather than his 3.4 mm would also account for the accommodation. Young's radii of curvature for the accommodated lens are appropriate parameters, but only if the thickness of the lens does not change.

Young's use of images reflected by the anterior cornea to establish that the changes in corneal curvature cannot account for accommodation is of considerable interest. He failed to note, however, the much fainter images reflected by the lens surfaces. Purkinje discovered these in 1819. Langenbeck in 1849 and Cramer in 1853 observed that the image due to the anterior surface grows smaller and moves forward when the eye accommodates, meaning that the surface becomes more curved. Helmholtz (1909) found this also and that the posterior surface grows more curved and the thickness increases a little.

## 5. Presbyopia

As well as the amplitude of accommodation measurements on himself and Wollaston, Young noted that Mr Abernethy (age not given) has 12 D, a "young" lady has 9D and a "middle aged" lady has 3.3D. Young suggested that "the faculty diminishes in some degree, as persons

advance in life" (p. 52). This could imply that Young was the first to recognize loss of accommodation with ageing. However, in 1795 Home wrote "*The change that takes place in the eye at an advanced period of life, by which it loses its adjustment to very near, and very distant objects, ...*" (Home, 1795) so it seems that there was already some degree of understanding of presbyopia. Young himself, in his earlier paper on vision (Young, 1793), had remarked (p. 177) "*It has been observed that the central part of the crystalline becomes rigid by age, and this is sufficient to account for presbyopia ...*"

## 6. Monochromatic aberrations

In his 1801 paper, Young made observations relating to the on-axis aberrations of his eye. He noted the through-focus appearance of small objects, which were dominated by the defocus (of course) and his astigmatism (pp. 43-44, Figure 3). He recognised the development during accommodation of what we now understand as negative spherical aberration by observing the shadows formed by slits in front of the eye. Further, using his optometer with 4 slits, he noted that the undoubled point on his optometer bar was further away for the lines corresponding to the outer pair of slits than for the lines corresponding to the central pair of slits (pp. 68-69). The latter observation was confirmed by one of two other observers. He went on to comment that the correction of spherical aberration may be due to the hyperbolic or elliptical (strictly hyperboloidal or ellipsoidal) form of the optical surfaces and to the existence of the lenticular gradient in refractive index.

In addition to axial aberrations Young considered off-axis imagery, writing (p. 46) "*But the whole of the retina is of such a form as to receive the most perfect image, on every part of its surface, that the state of the refracted pencil will admit*".

In a fascinating diagram (his Fig. 16, reproduced here as Figure 6) he summarised the results of off-axis ray-tracing through his eye model using the equations he developed in section IV. Since Young's right eye was myopic, the object field was a circular arc of 10" (25 cm) radius in front of the eye. The centres of ray bundles (chief rays) passed through the lens anterior vertex, corresponding to the position of the stop. He calculated first the positions of the tangential and sagittal image surfaces and what is effectively the position of the circle of least confusion for corneal imagery alone (curves 1-3), then the surfaces for imagery due to the cornea and the anterior surface of the crystalline lens (curves 4-6) and lastly for the whole eye (curves 7-9). In the lower part of the figure, curve 10 is a repetition of curve 9 (i.e. the locus of the circle of least confusion and is compared with curve 11, which Young says corresponds to the retina. Curve 12 is the supposed locus of the circle of least confusion if the lens showed refractive index variation. Young stated in reference to curves 10 and 11 (p. 47) "*It will appear that nothing more is wanting for their perfect coincidence, than a moderate diminution of density (refractive index) in the lateral parts of the lens. If the law, by which this*



density varies, were more accurately ascertained, its effect on the image might be calculated.....probably the image, thus corrected, would approach very nearly the form of the twelfth curve."

FIGURE 6 ABOUT HERE

Note that in spite of his earlier optimistic statement about the image quality on the retina, curves 10 and 11 (and also 11 and 12) do not correspond exactly and in fact his diagram suggests that there is compound myopic astigmatism in the periphery. Direct measurement from his plots (curves 7-9) gives the estimated reduced vergence errors shown in Fig. 7. The vergence errors are referenced to the exit pupil of the eye, lying 3.114 mm from the anterior cornea. The tangential and sagittal reduced vergence errors are given by the equations  $L_t' = n'/t' - n'/r'$  and  $L_s' = n'/s' - n'/r'$ , and (oblique) astigmatism is  $L_t' - L_s'$ . Here  $n'$  is the refractive index (4/3) and  $s'$ ,  $t'$  and  $r'$  are the (positive) distances from the exit pupil centre to the sagittal image surface, the tangential image surface and the retina, respectively.

FIGURE 7 ABOUT HERE

### Commentary

Young did not demonstrate the usual positive spherical aberration in the unaccommodated eye, probably because none of his subjects had sufficient amounts under the conditions of his experiments. However, in view of changes observed upon accommodation, it is reasonable to say that he was the first to demonstrate the change in magnitude and sign of spherical aberration upon accommodation. Using his "Aberroskop", Tscherning (1894; 1900) was possibly the next to show that the sign of aberration changed with accommodation. This was again observed in the middle of the 20<sup>th</sup> century (Berny, 1969; Ivanoff, 1956; Jenkins, 1963; Koomen, Tousey, & Scolnik, 1949; Schober, Munker, & Zolleis, 1968) and subsequently in numerous studies with the benefit of modern instrumentation in the last 15 years.

Young was the first to point out the existence of oblique astigmatism in the peripheral visual field. As noted above, Young's claim that the retina receives the "most perfect" image is not supported by his own results. When the sagittal and tangential images are superimposed upon the retina of Young's Fig. 16, which has a radius of curvature of approximately 11.3 mm, both of the surfaces are in front of the retina (Figure 7). Our raytracing of thin beams with an optical design program indicates that the sagittal image shell should be slightly behind the retina. While one may quibble about this and wonder to what extent Young's Fig. 16 was qualitative rather than quantitative (e.g. the astigmatic image surfaces are shown as extending up to the axial position of the lens), its importance lies in his pioneering recognition of the large

amounts of peripheral astigmatism present in the human eye and his determination of its approximate magnitude.

For out-of-the-eye raytracing, the model shows considerable relative myopia eg 1.6 D for 30° field angle (Figure 8). Young suggested that the average of the sagittal and tangential surfaces would be close to the retina if the refractive index variation was more accurately obtained.

FIGURE 8 ABOUT HERE

Measurements of peripheral refractions were undertaken in the early twentieth century using a variety of techniques (Ames & Proctor, 1921; Sheard, 1921-1922), including objective refraction with a coincident optometer (Ferree, Rand, & Hardy, 1931). Nowadays there are many studies of peripheral refraction spurred by the possibility that it may be implicated in the development of myopia (Hoogerheide, Rempt, & Hoogenboom, 1971). While emmetropes and hypermetropes tend to have relative negative (myopic) overall peripheral refractions and myopes tend to have relative positive (relative hypermetropic) peripheral refractions, generally the tangential and sagittal refractions have excess positive and negative power relative to the on-axis refraction (Atchison & Smith, 2000).

## 7. Chromatic aberration

In his 1801 paper, Young estimated longitudinal chromatic aberration with his optometer. Different parts of the spectrum viewed through a prism were isolated. Red light was focused at 12" and white and yellow light were focused at 11", a difference equivalent to a lens of focal length 132" (0.3 D power). Young could not observe any aberration of the violet rays (presumably determined relative to a yellow or white light), but conceded that this "may be, in part, owing to their faintness" (p. 51).

### Commentary

Newton had earlier demonstrated the existence of chromatic aberration in the eye but did not quantify it (Shapiro, 1984). Using contemporary estimates of ocular refractive indices and dimensions, together with Newton's imperfect formula for dispersion, Maskelyne (1789) calculated that the longitudinal chromatic aberration across the visible spectrum was about 1.5 D. Young's difference between red and yellow/white was approximately correct, but the refraction for violet light, assigning it a wavelength of 450 nm, should have been approximately 1.0 D more negative than for yellow/white light (Atchison & Smith, 2000), and undoubtedly the low luminance for this colour was responsible for the inaccurate measurement. Probably Young made these observations in or near the Northern winter months using natural lighting, because he wrote "At a more favourable time of the year, it would not be difficult to

ascertain, by means of the optometer the dispersive power of the eye, and of the different parts, ..." (p. 51). It may be that his expectations were biased by the earlier conjecture of Ramsden, that a medium of gradually changing refractive index, such as the crystalline lens, might not introduce any dispersion (Home, 1795). In a later paper, however, Young (1802a) found an aberration between extreme red and violet of about 1.3 D, again using his optometer.

Fraunhofer made the first reliable measurements on the difference in the focal length of the eye for extreme spectral colours by observations of a prismatic spectrum through an achromatic telescope, the eyepiece of which carried a cross-hair. Fraunhofer's estimate for his own eye was 1.5-2.0 D (wavelength range 656 to 434 nm) (Helmholtz, 1909). Helmholtz obtained a value of 1.7 D between red and violet (wavelength range not stated) and considered that the chromatic dispersion of the eye is greater than that of pure water. Longitudinal (although not transverse) chromatic aberration has since been shown to be remarkably consistent between different individuals (Atchison & Smith, 2000).

## 8. Depth-of-focus

In section X of his 1801 paper, Young noted that his aphakic subjects had a range of distances over which an unspecified target was seen "with perfect distinctness", yet had a fixed intersection of the apparently doubled bars observed with his optometer (p. 66). Four of his subjects showed dioptral ranges of 2.3 D to 23 D. Young mentioned Home's aphakic patient (Home, 1795) who had a 15 D range with a 1.9 mm diameter aperture. Young claimed that he himself had a range of 25D for this aperture size, which was reduced to 16 D when he relaxed his eye. This led him to make a contrast between "distinct" vision and "perfect" vision. He commented (p. 67) "*It is obvious that vision may be made distinct to any given extent, by means of an aperture sufficiently small, provided at the same time, that a sufficient quantity of light be left, while the refractive powers of the eye remain unchanged*".

### Commentary

This point covers what we call depth-of-focus and how it is affected by pupil size. Most of the limits mentioned are very high and it can be only supposed that the target detail was large. Young's comments on the use of small apertures foreshadow the use of the pinhole test to distinguish between poor vision due to refractive error and that due to amblyopia or pathology. The quotation given above suggests that Young was thinking almost entirely in terms of geometrical blur circles on the retina and that he failed to consider the possibility of increasing diffractive blur as the pupil size was reduced. It was not until some thirty years later that Airy (1835) fully described the diffraction pattern for a circular aperture.

Numerical estimates of depth-of-focus vary substantially with the methods used to assess it, as has been shown in, for example, recent studies of based on "just noticeable", "just troublesome" and "just objectionable" or other blur criteria (Atchison, Fisher, Pedersen, & Ridall, 2005; Ciuffreda et al., 2006). Young is apparently distinguishing between "perfect vision", when no blur at all is detectable and "distinct" vision", where although some blur is perceptible, either the vision is acceptable or it is still possible to read the given text.

## 9. Instrument accommodation

Young wrote regarding the use of his optometer (p. 36) "*Few can bring their eyes at pleasure to the state of full action, or of perfect relaxation; and a power two or three degrees [scale intervals] lower than that which is thus ascertained, will be found sufficient for ordinary purposes*." This seems to be the first mention of the difficulty many pre-presbyopic people have in relaxing accommodation when using visual optical instruments (Rabbetts, 2007).

## 10. Gradient index of the lens

At several points in his 1801 paper, Young considered the possibility that the refractive index of the lens could vary, reducing from the centre towards the edge of the lens. He wrote that the gradient index affects the equivalent refractive index so that the lens acts as a smaller (more curved) lens. He developed a model for this in which a centre of fixed index was surrounded by a region in which the refractive index reduced progressively as  $R^q$ , where  $R$  is the distance from the centre and  $q$  is a negative number related to the outer diameters of the fixed and gradient refractive index regions. He gave an equation for the variable index that would allow a spherical surface to be aberration-free (p. 32). He considered that the gradient index would have a role in improving peripheral retinal imagery (p. 47) and mentioned Ramsden's speculations that it would reduce reflections and, perhaps, chromatic aberration (Home, 1795). Young's contributions to gradient index are covered elsewhere (Atchison & Charman, submitted).

### Commentary

Young seems to have been the first to describe the lens as having a gradient refractive index. While commenting on its effect on peripheral imagery, he made no comment on how it might be involved with changing aberration upon accommodation. His refractive index of 1.436 (14/13 relative to the surrounding 4/3 index media) is the first use of an equivalent refractive index (p. 42). Gullstrand (1909) developed this work further in the early part of the 20<sup>th</sup> century with schematic eye models containing lenses in the form of shells of different refractive indices; this was a

simple way of incorporating gradient index effects amounting to 6 D in an unaccommodated eye and to 15 D in an eye accommodating by 9 D (Atchison & Smith, 2004). We do not yet know the accurate form of the index gradient, how it changes with ageing, or its effects on lens power, aberrations and accommodation, but this has not stopped us refining Young and Gullstrand's modelling eg (Goncharov & Dainty, 2007; Navarro, Palos, & Gonzalez, 2007a, 2007b; Smith, Pierscionek, & Atchison, 1991).

## 11. Peripheral vision

Young gave values for the extent of his visual field as 50° upwards, 60° inwards, 70° downwards, and 90° outwards, and mentioned the facial limitations for these (pp. 44-45). William Wollaston's eye "*has a larger field of view, both vertically and horizontally, but nearly in the same proportions, except that it extends further upwards*". Young mentioned the fact that the retina extends further on the nasal side than on the temporal side (Snell & Lemp, 1998).

Young determined the position and extent of the position of the blind spot, and, no doubt using his ocular parameters, converted these to distances on the retina (p. 47): "*From the experiment here related, the distance of the centre of the optic nerve from the visual axis is found to be 16 hundredths of an inch [4.1 mm]; and the diameter of the most insensible part of the retina, one-thirtieth of an inch [0.85 mm].*" This means that the blind spot lay at about 14° from the visual axis and that it had a diameter of about 3°, the latter being a considerable underestimate.

Young commented on the loss of vision away from the visual axis: "*But the whole extent of perfect vision is little more than 10 degrees; or, more strictly speaking, the imperfection begins within a degree or two of the visual axis, and at the distance of 5 or 6 degrees becomes nearly stationary, until, at a still greater distance, vision is wholly extinguished. The imperfection is partly owing to the unavoidable aberration of oblique rays, but principally to the insensibility of the retina*" (p. 45).

### Commentary

Young's limits to the field of vision were reasonable. He described the loss of form vision away from the axis. He correctly attributed the majority of this loss as due to neural rather than optical limitations, although it should be mentioned that the limitations imposed by the peripheral optics are very important for some tasks such as detection (Wang, Thibos, & Bradley, 1997).

Wade (1998) provides a historical context for Young's investigations of peripheral vision. In 1775, Harris had suggested that the field of vision extended to at least 60° in all directions. Mariotte discovered the blind spot in 1668, and he and others had determined its position, if not its extent, in the visual field. The "imperfection" of peripheral vision had been noted by several other people back to Ptolemy in the second century.

## 12. Eye movement

Young referred to the eye being able to rotate in all directions by about 55° (p. 46), which is a considerable overestimate for most people. It is usually considered that although the eyes can scan a field extending up to 45° from the straight-ahead or primary position, in practice eye movements rarely exceed 20°, fixation on more peripheral objects being achieved by a combination of head and eye movements. He made a brief comment on binocular vision in relation to possible artefacts in measurements implying that he understood the close links between accommodation and convergence: "*The eyes sympathize perfectly with each other; and the change of focus is almost inseparable from a change of the relative situation of the optic axes*" (p. 54). Interestingly, he made no mention of accommodative miosis.

## 13. Anatomy and Physiology

Having established to his satisfaction that accommodation is produced by change in lens shape, at the end of section X of his 1801 paper Young considered how this may occur. He attributed muscular aspects to the fibres of the lenses and attempted to trace nerves to the lens: "*I have sometimes imagined that I have succeeded: but I cannot positively go further than to state my full conviction of their existence*" (p. 74). He also attempted electrical stimulation of animal lenses, but was not disappointed that this failed to change the shape (p. 73-74). Section XI was devoted to comparative anatomy of the lens and its surrounding structures, which is outside the scope of this paper.

### Commentary

About 1848, Bowman and Brücke independently discovered the ciliary muscle and concluded that accommodation was produced by its contraction (Sheard, 1921-1922). This led to Helmholtz's theory of accommodation (1909): "*On contraction, the ciliary muscle could pull the posterior end of the zonule forwards nearer the lens and reduce the tension of the zonule. ... If the pull of the zonule is relaxed in accommodating for near vision, the equatorial diameter of the lens will diminish, and the lens will get thicker in the middle, both surfaces becoming more curved. ... It would seem that the changes in the form of the lens could be explained on this basis.*". With some modifications, and despite the challenges of Tscherning (1900) and his successors, this remains the widely understood mechanism of human accommodation.

Young's hopeful search for lenticular nerves was doomed to disappointment. However it is important to note his remark (p. 78) "*The lens itself, when taken out of the eye, in its capsule, has elasticity enough to reassume its proper figure, on the removal of a force that has compressed it. The capsule is highly elastic: and since it is laterally fixed to the ciliary*

zone, it must cooperate in restoring the lens to its flattest form.” While too much credit should not be given to Young, it would seem that he was groping here towards the ideas of the importance of lens and capsule elasticity which were to be central to Fincham’s development of accommodation theory (Fincham, 1937).

## Discussion

It can be seen that Young’s contributions to visual optics extend much further than accommodation and astigmatism. His experiments showed remarkable ingenuity and dexterity. It is pertinent to ask, however, why he did not follow up his early insights in this area by further work during the more than twenty years of life that remained before him. In part this may be because it seems that his reputation had been severely damaged by the vitriolic attacks of an initially-anonymous critic, Henry Brougham (1778–1868). Young had earlier casually made some uncomplimentary remarks about Brougham’s own mathematical work and the latter retaliated by vigorously attacking his critic, charging him both with inconsistency and triviality. Commenting on Young’s 1801 Bakerian Lecture on light and colour (Young, 1802b), Brougham (1803) wrote in the “Edinburgh Review” *“The author of this paper introduced himself to the literary world by a few desultory remarks upon a theory, which he appeared to think new, but which had previously been exposed and refuted – the muscularity of the crystalline lens. Soon after this, he retracted his opinion, and a year or two ago he again brought it forward. We do not know whether or not he has once more abandoned it ... Let it teach him a becoming caution in the publication of his theories.”* Brougham (1804) was even more scathing regarding the contents of the 1803 lecture on interference of light (Young, 1804): *“As this paper contains nothing which deserves the name of experiment or of discovery, and as it is, in fact, destitute of every species of merit...”* These words, and the further fierce criticisms which followed, seem to have deeply wounded Young, with the consequence that he eventually decided to refrain from further work in the sciences, apart from medicine. He did not keep this resolution completely but his subsequent publications were usually anonymous and he does not appear to have returned to original work in vision. It may also be that he felt that he might lose patients in his medical practice if it appeared that he was not concentrating on medical studies.

Perhaps, though, these suggestions do not provide the full story, as Young himself concedes in his autobiographical sketch (Hilts, 1978). There, writing in the third person, he formulates his credo in a sentence of Proustian length and complexity: *“Whether the public would have benefited by his confining his exertions within narrow limits is a question of great doubt: his own idea was, that the faculties are more exercised, and therefore probably more fortified, by going a little beyond the rudiments only, and overcoming the elementary*

*difficulties, of a variety of studies, than by spending the same number of hours in any one pursuit, and it was generally more his object to cultivate his own mind than to acquire knowledge for others in departments which were not his immediate concern: while he thought with regard to modern doctrines, of the division of labour, that they applied much less to mind than to matter, and that while they increased the produce of a workman’s physical strength, they tended to reduce his dignity in the scale of existence from a reasoning being, to a mere machine.”*

Whatever the motivation of this complex man, his studies remain relevant to many of the topics which currently engage visual scientists. Although his work was, in some ways, overshadowed by the later, much more thorough, studies of Helmholtz, it was Helmholtz himself who rightly recognised the value of Young’s somewhat-neglected contributions and brought them back to general notice. Donders (1864) was another admirer, noting rather sadly that *“the force of Young’s experiments was not understood...”* (pp. 10-11). It was left to Tscherning (1907), who was so much of an enthusiast that he translated all of Young’s optical works into French, to give him the ultimate accolade as *“the father of physiological optics”*.

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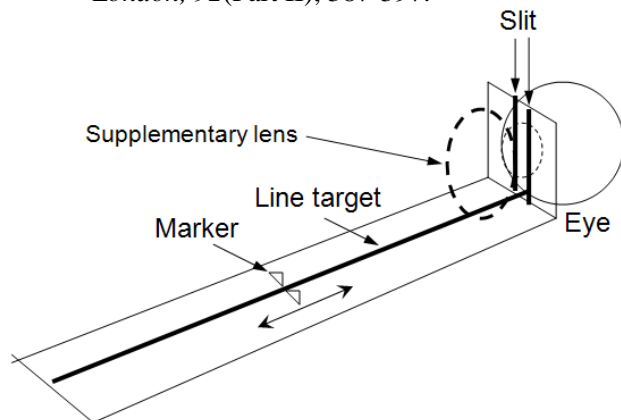


Figure 1. Schematic diagram of Young's optometer. For clarity the width of the target line has been exaggerated. Since each out-of-focus point on the target line was seen as doubled by an amount proportionate to the defocus, only the point on the line which was conjugate with the retina was that which was seen single. The marker was therefore moved to the position where the subject saw two lines crossing. Young used slit widths between about 1/40 and 1/10" (0.6 and 2.5 mm) "divided by spaces somewhat broader, so that each observer may choose that which best suits the aperture of his pupil". With the arrangement as shown, the measured refraction was for the horizontal meridian: for other meridians the whole apparatus was appropriately rotated about the target line.

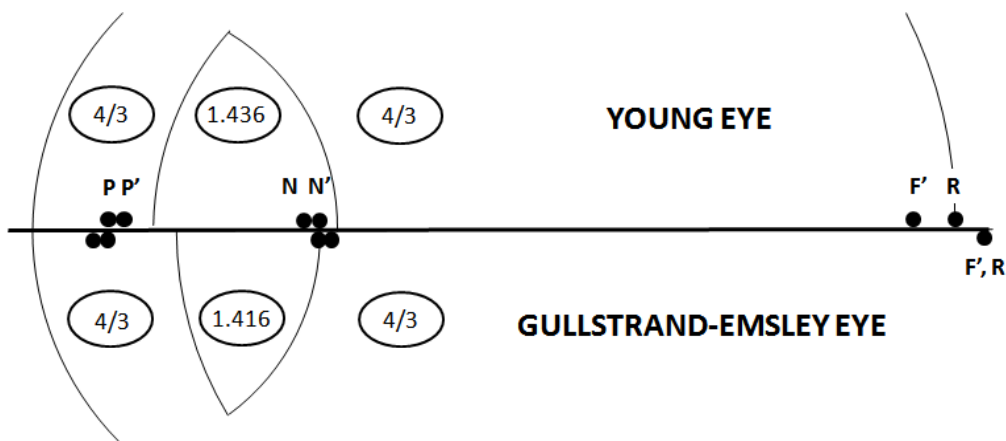


Figure 2. Schematic model of Young's parameters for his own myopic eye in unaccommodated vision (far point 254 mm in front of cornea). The relaxed Gullstrand-Emsley eye is included for comparison. Principal points are given by  $P$  and  $P'$ , nodal points by  $N$  and  $N'$ , the posterior focal point by  $F'$  and the retina by  $R$ . Young's retina is given a radius of curvature of  $-11.3$  mm (see Figure 6 caption).

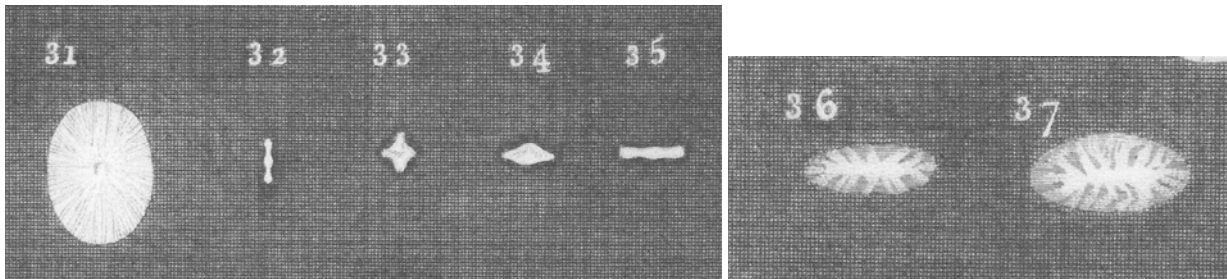


Figure 3. Appearance of the through-focus retinal point-spread function as sketched by Young (his Figs. 31 to 37).



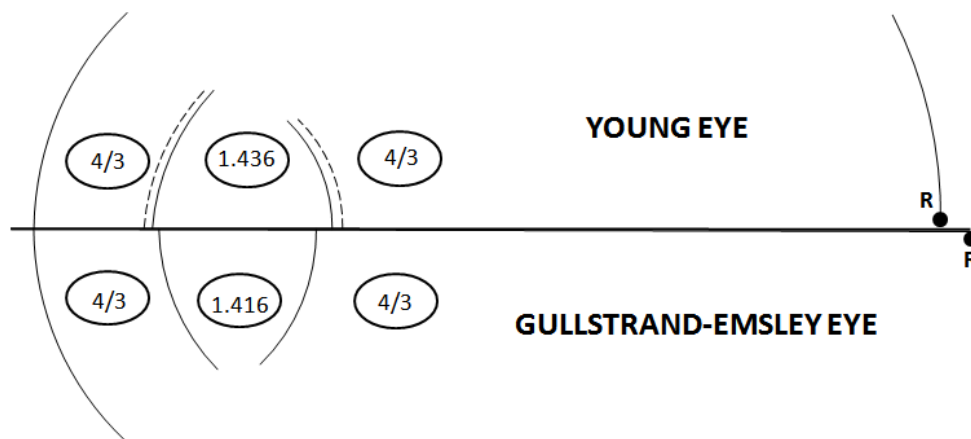


Figure 4. Schematic model of Young's eye parameters in accommodated vision (10 D accommodation, near point 72.6 mm in front of the cornea). The accommodated Gullstrand-Emsley eye is included for comparison (8.6 D accommodation). As discussed in the text, Young used different assumptions at various places in his paper. The dash curves show the lens surfaces of Young's eye if the lens increased in thickness by 0.02" (0.508 mm) with changes in anterior chamber depth and vitreous length in proportion to changes in surface curvature relative to the accommodated state; this version is 0.11 mm too short.

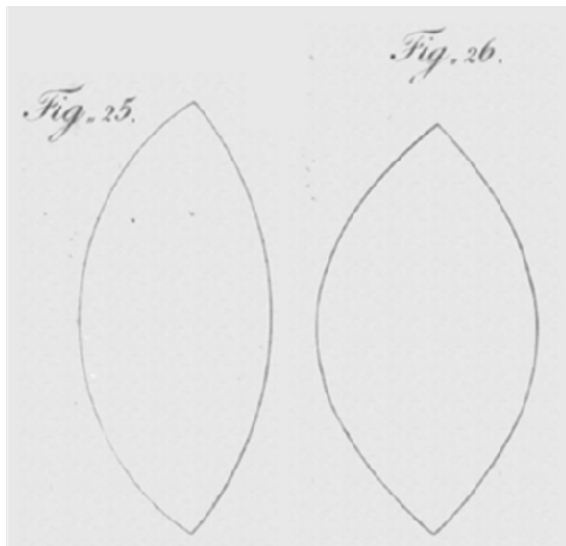


Figure 5. Young's figures showing the unaccommodated lens (his Fig. 25) and accommodated lens (his Fig. 26).

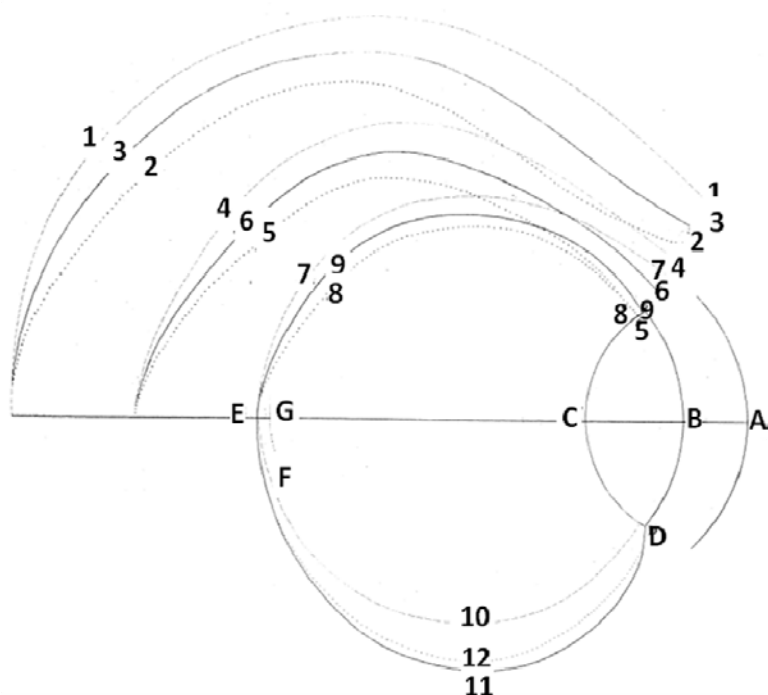


Figure 6. The astigmatic image surfaces after Young (his Fig.16). Numbers and letters have been made more legible. For explanation, see text.

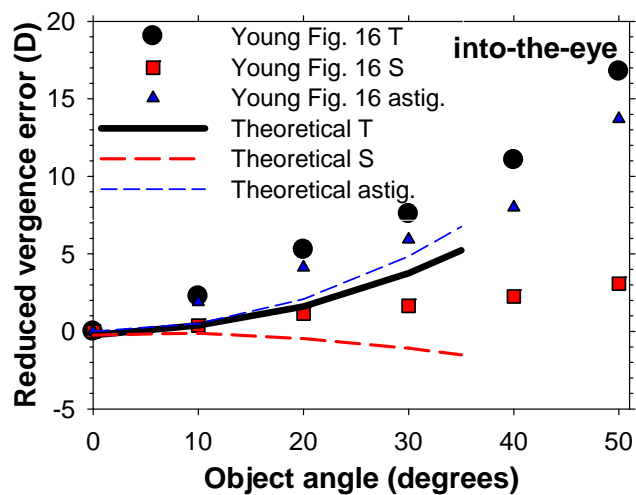


Figure 7. Into-the-eye reduced vergence errors from Young's Fig.16 (our Figure 6). These are referenced to the exit pupil of the eye which is 3.114 mm inside the eye. For comparison, we have shown theoretical results from raytracing into the eye using a retinal radius of curvature of 11.3 mm; as this fit is reasonably accurate to only 35°, we have traced only to this angle. Positive values of T and S correspond to the image surfaces being anterior (in front of) to the retina, and this would be corrected by placing negative powered lenses next to the cornea along the peripheral chief rays. Positive values of astigmatism correspond to the tangential image being anterior to the sagittal image.

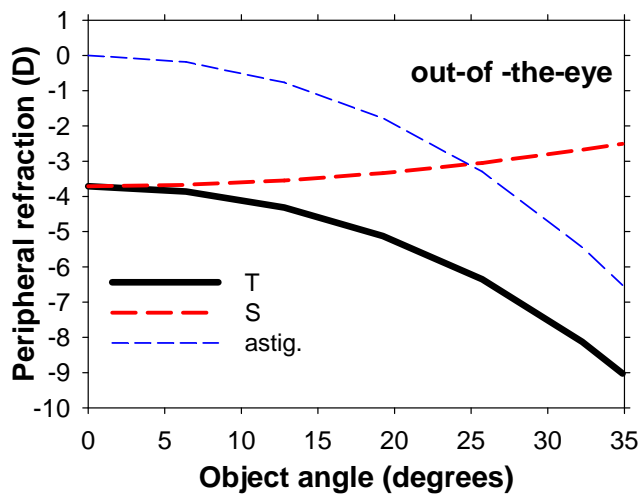


Figure 8. Peripheral refraction as a function of field angle of Young's model eye for raytracing out-of-the-eye. These are referenced to the entrance pupil of the eye. Based on its shape in Figure 4, a 11.3 mm radius of curvature has been used for the retina. The retina flattens beyond about 35° object angle (see Figure 4) and the tangential and sagittal refractions would actually move in the negative direction.